Neutral Naturalness
— Phenomenology —

HXSWG Exotic Higgs Decays Workshop
SLAC

7 November 2016

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University of Maryland

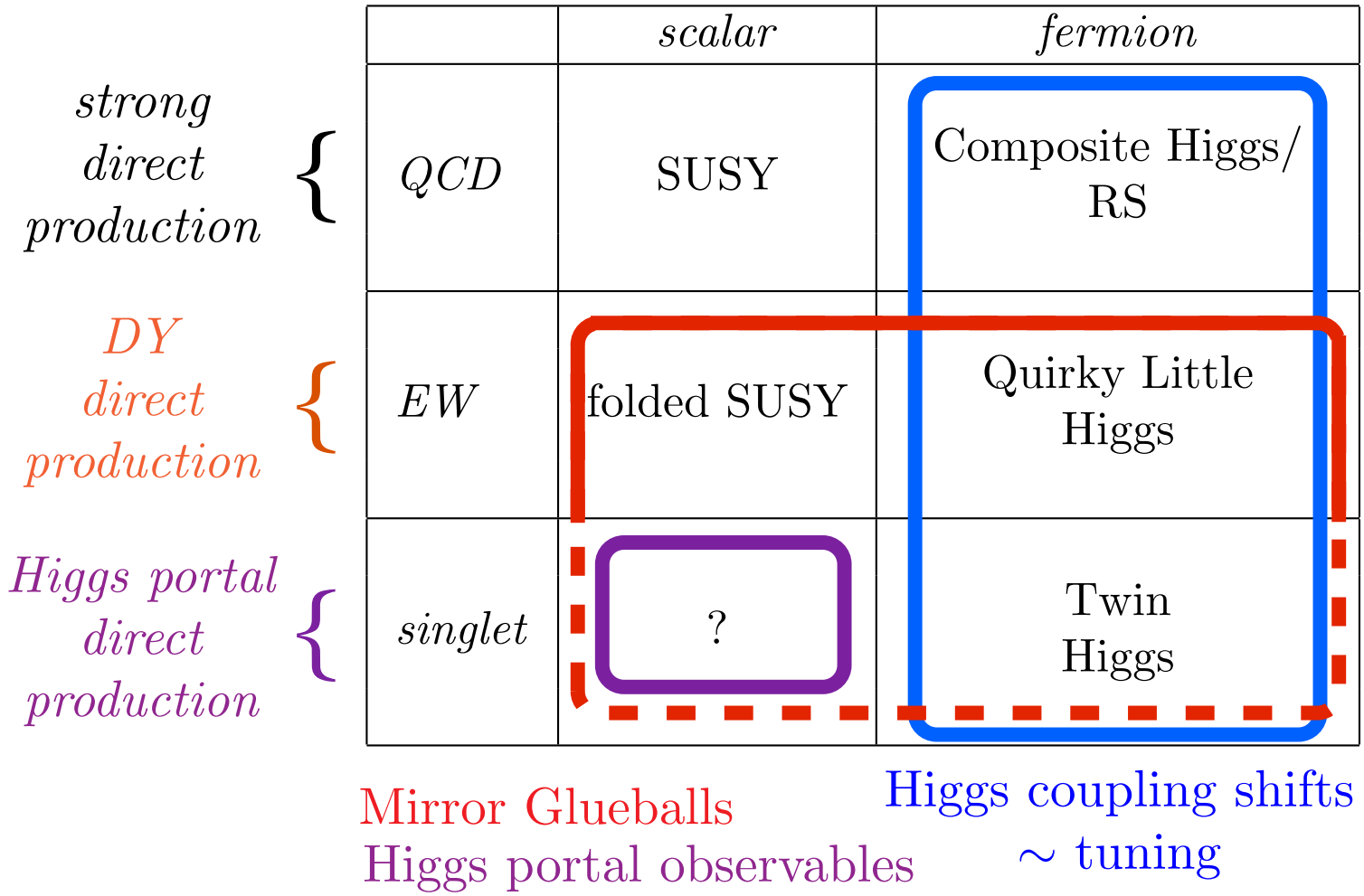
Neutral Naturalness Phenomenology

Mostly determined by
(a) gauge charge of top partners (EW or singlet)
(b) lightest hadrons in hidden sector spectrum.

Will discuss canonical possibilities for hidden sector:
glueballs, bottomonia

Other possibilities exist
(e.g. hidden pions decaying to SM via vector portal)

Neutral Naturalness Phenomenology



Neutral Naturalness with Light Mirror Glueballs

Light Mirror Glueballs

Consider scenario where hidden QCD sector has no light quarks.

This is `required' for EW top partners (FSUSY, QLH) by **LEP constraints**.

One of the cosmologically motivated possibilities for Twin Higgs.

Craig, Katz, Strassler, Sundrum 1501.05310

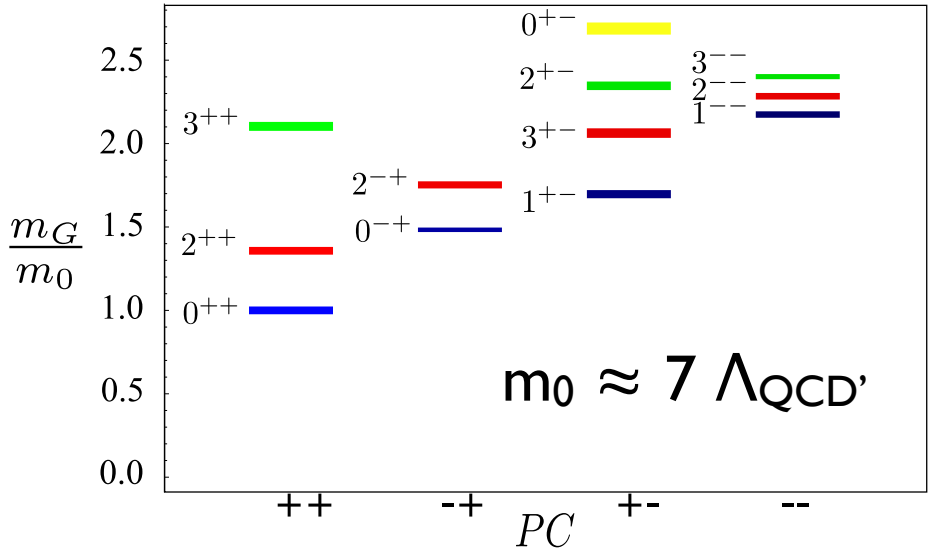
DC, Verhaaren 1506.06141

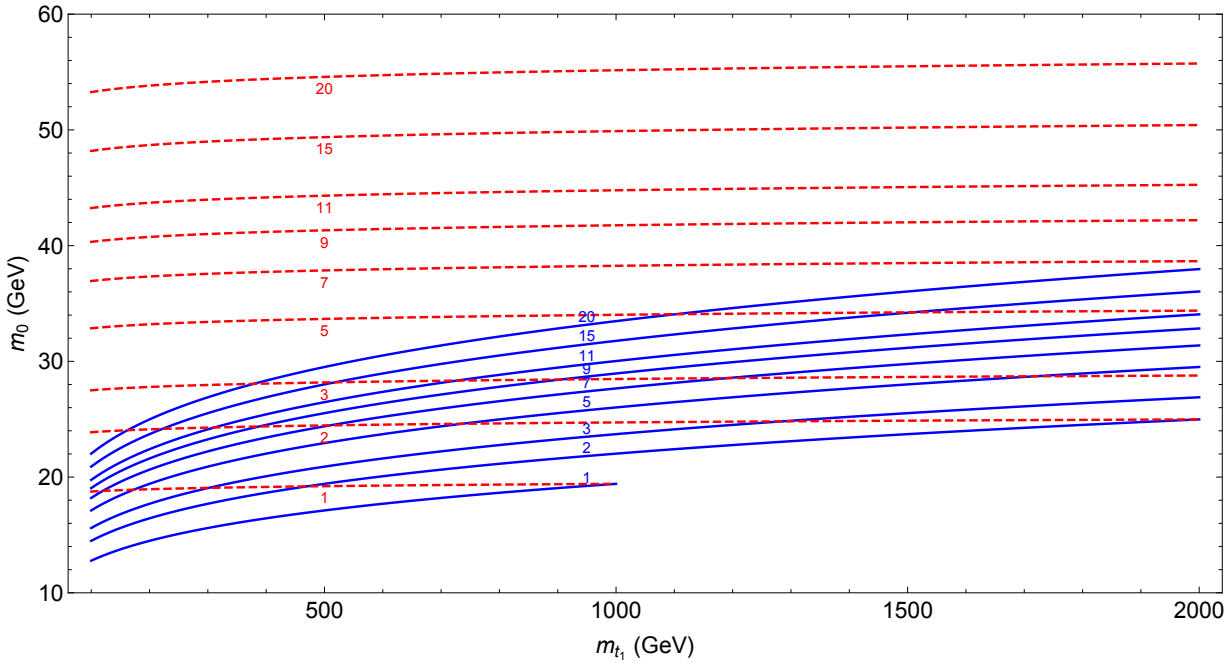
Light Mirror Glueballs

top partners

maybe other states

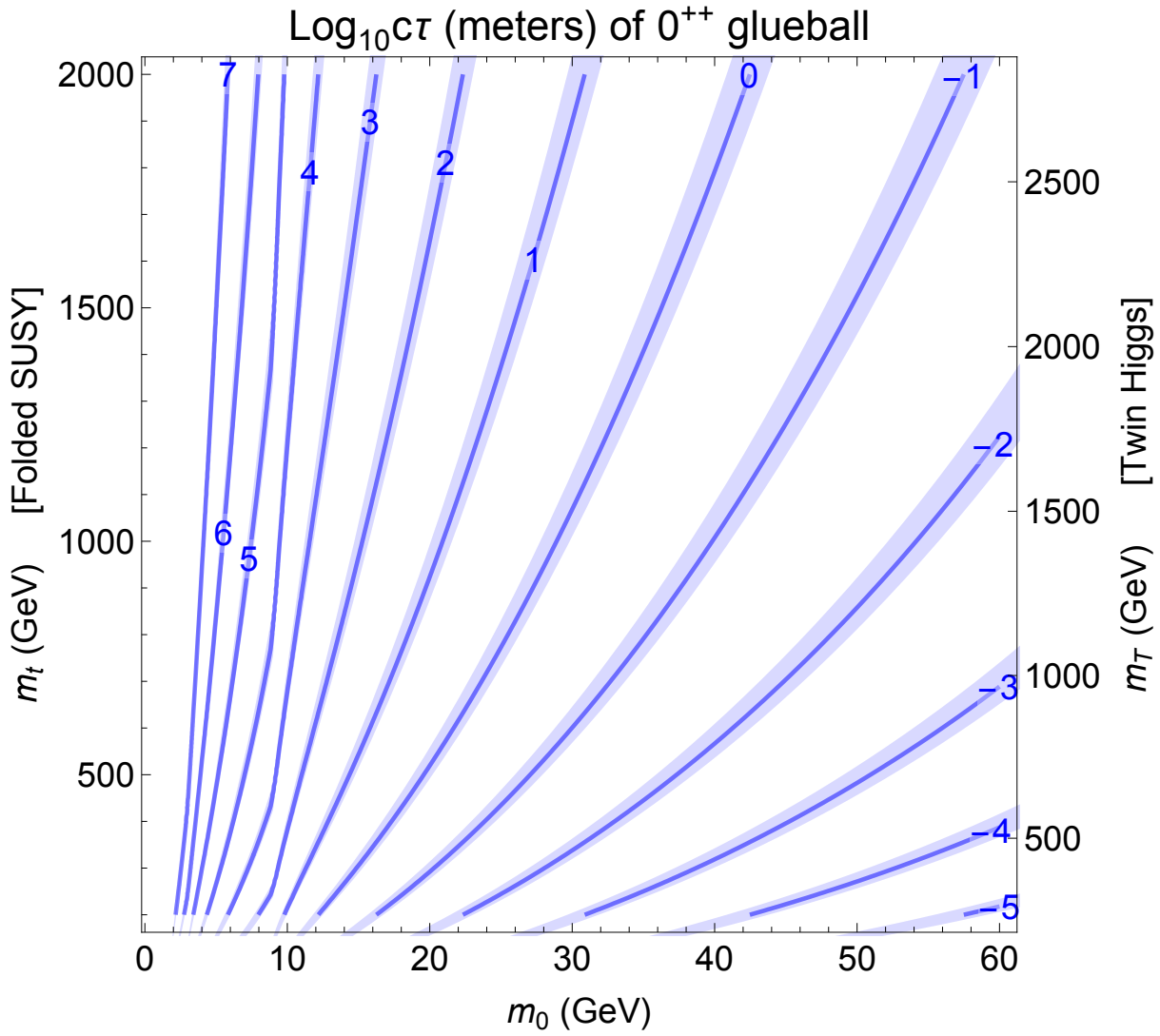
QCD' glueballs
< ~ 60 GeV





Z_2 symmetry
&
RG running
→
$m_0 < 60$ GeV

Light Mirror Glueballs



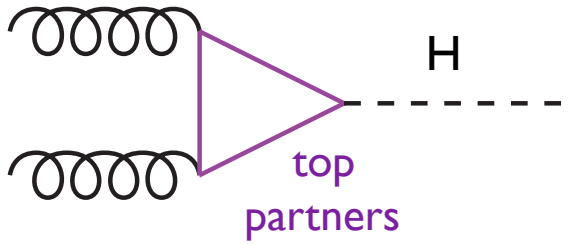
Large range of lifetimes

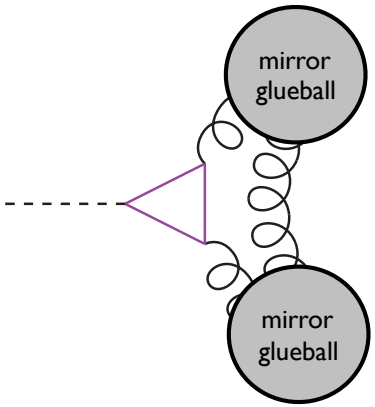
0911.5616 Juknevich

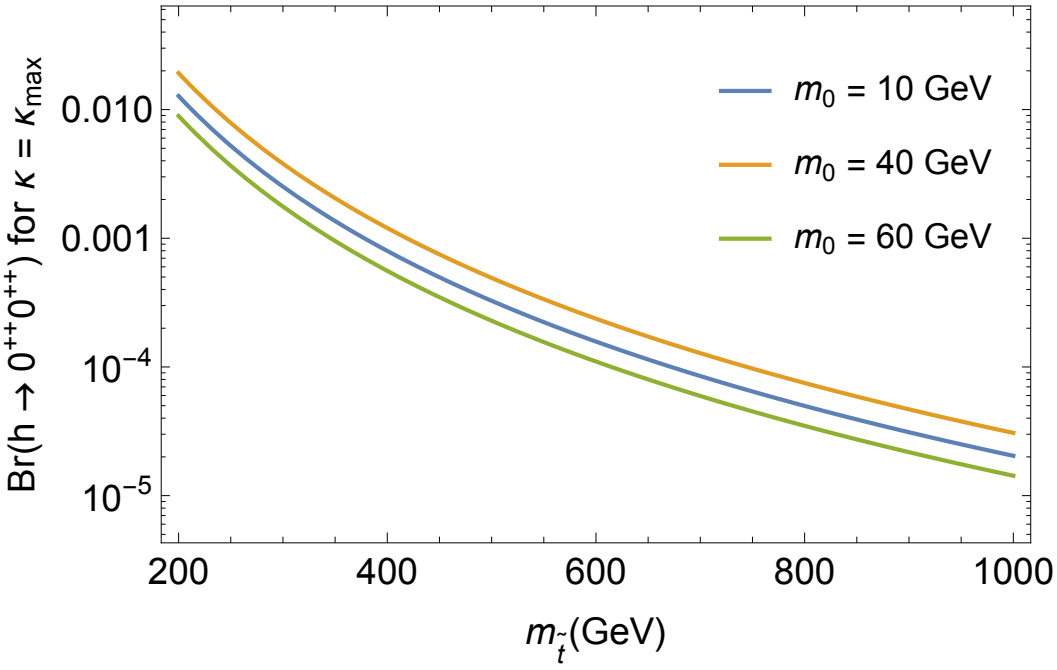
Exotic Higgs Decays

Higgs talks to mirror glue via top partner loops:

$$\mathcal{L}^{(6)} = \frac{\alpha_v\, y^2}{3\pi\, M^2}\, H^\dagger H\, \mathrm{tr}\, \mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}$$







Large signal rate of conspicuous LLPs

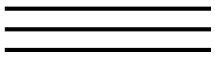
Neutral Naturalness with Light Mirror Glueballs and/or Mirror Bottomonia

Light Mirror Glueballs and/or Bottomonia

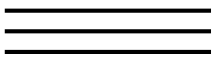
In Twin Higgs Scenarios, some or all of the mirror quarks can be light (singlets)

Fraternal TH: only mirror top and bottom

top partners

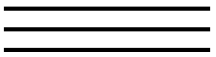


bottomonia



QCD' glueballs

top partners



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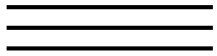


bottomonia

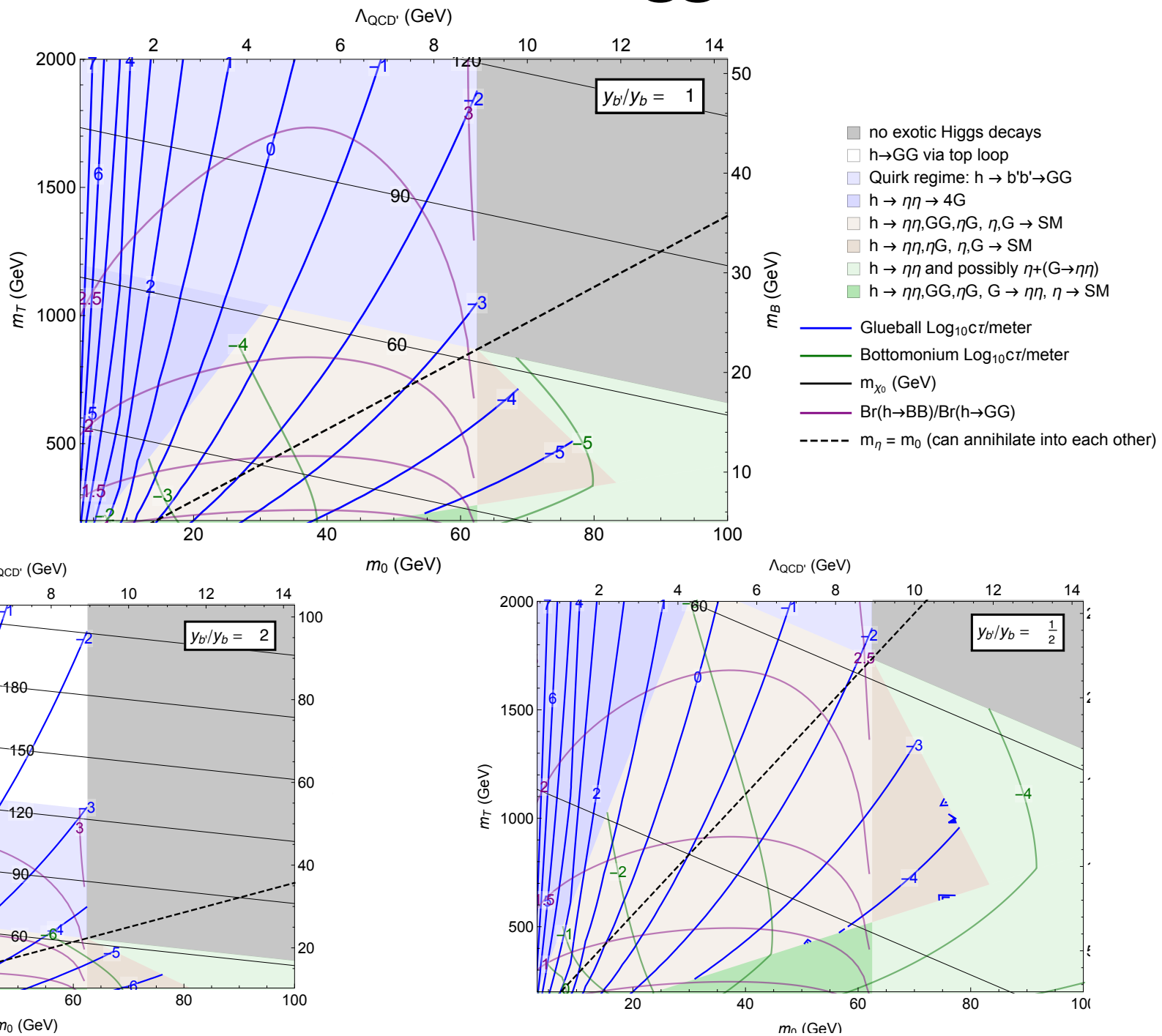
Complicated phase space of theory!

Craig, Katz, Strassler, Sundrum 1501.05310

DC, Tsai 1701.xxxxx

Fraternal Twin Higgs

DC, Tsai 1701.xxxxx



Exotic Higgs Decays (Twin Higgs)

Branching ratio to glueballs roughly same as in FSUSY

Branching ratio to mirror bottoms is via yukawa rather than top partner loop → potentially orders of magnitude larger

Complicated nonperturbative dynamics, especially when glueballs and bottomonia mix

Lifetime of bottomonia tends to be shorter than glueballs, but still displaced.

→ **LLP searches for all lifetimes motivated for all LLP masses!**

Modeling non-perturbative dynamics of the Hidden Sector

Modeling Exotic Higgs Decays to Glueballs

Hadronization is hard even in the SM (where we can calibrate)

For Hidden Valleys which are similar to SM QCD we can rescale QCD to simulate hadronization with reasonable confidence.

For scenarios with light mirror bottoms,
SM -onia provide some guidance

Light glueballs? We have no idea how they hadronize!

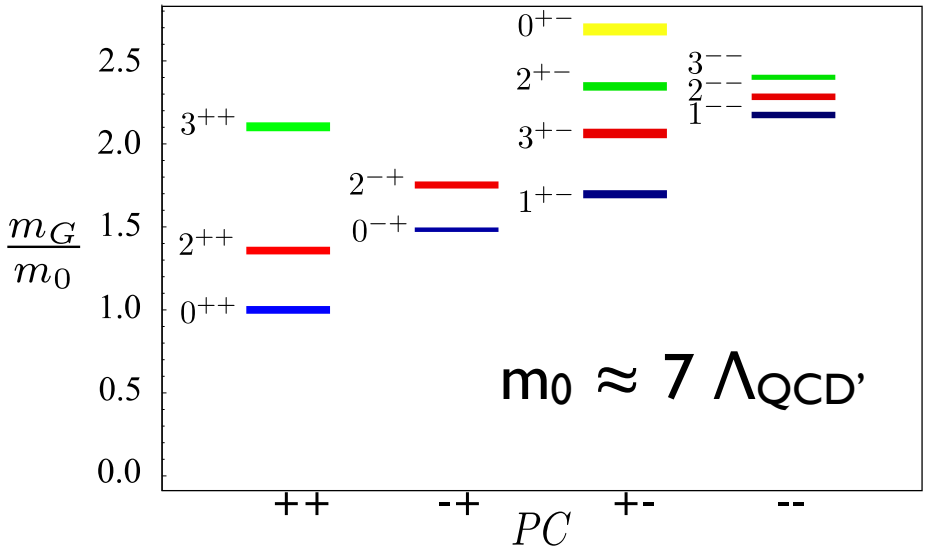
Modeling Exotic Higgs Decays to Glueballs

For exotic Higgs decays, we can study phenomenology by pessimistically assuming 2 glueballs per decay.

(How much more could we have?)

The 0++ glueball has shortest lifetime and is usually the only observable state.

What fraction of glueballs is 0++?



Thermodynamic expectation is ~30-50%, but could be very different. **Need to consider range of possibilities.**

Modeling Exotic Higgs Decays to Glueballs

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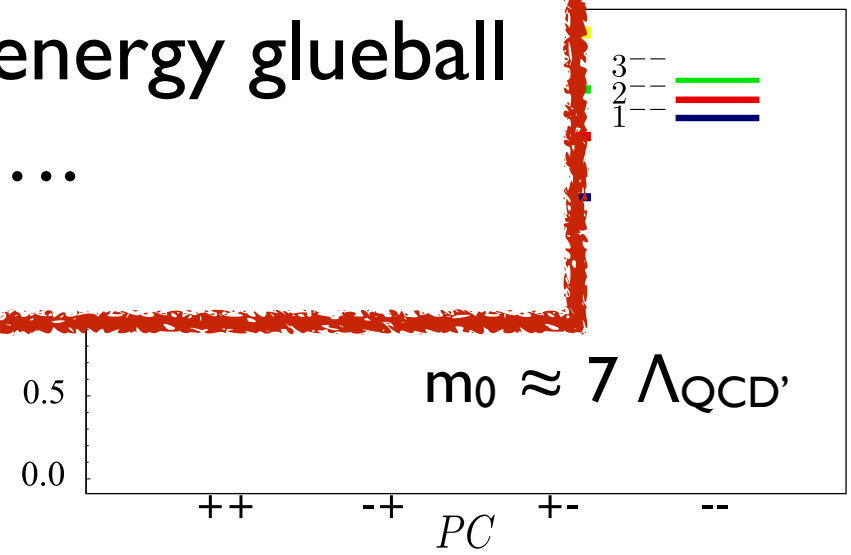
The G
lifetin

Details of hadronization become even more critical for higher-energy glueball production….



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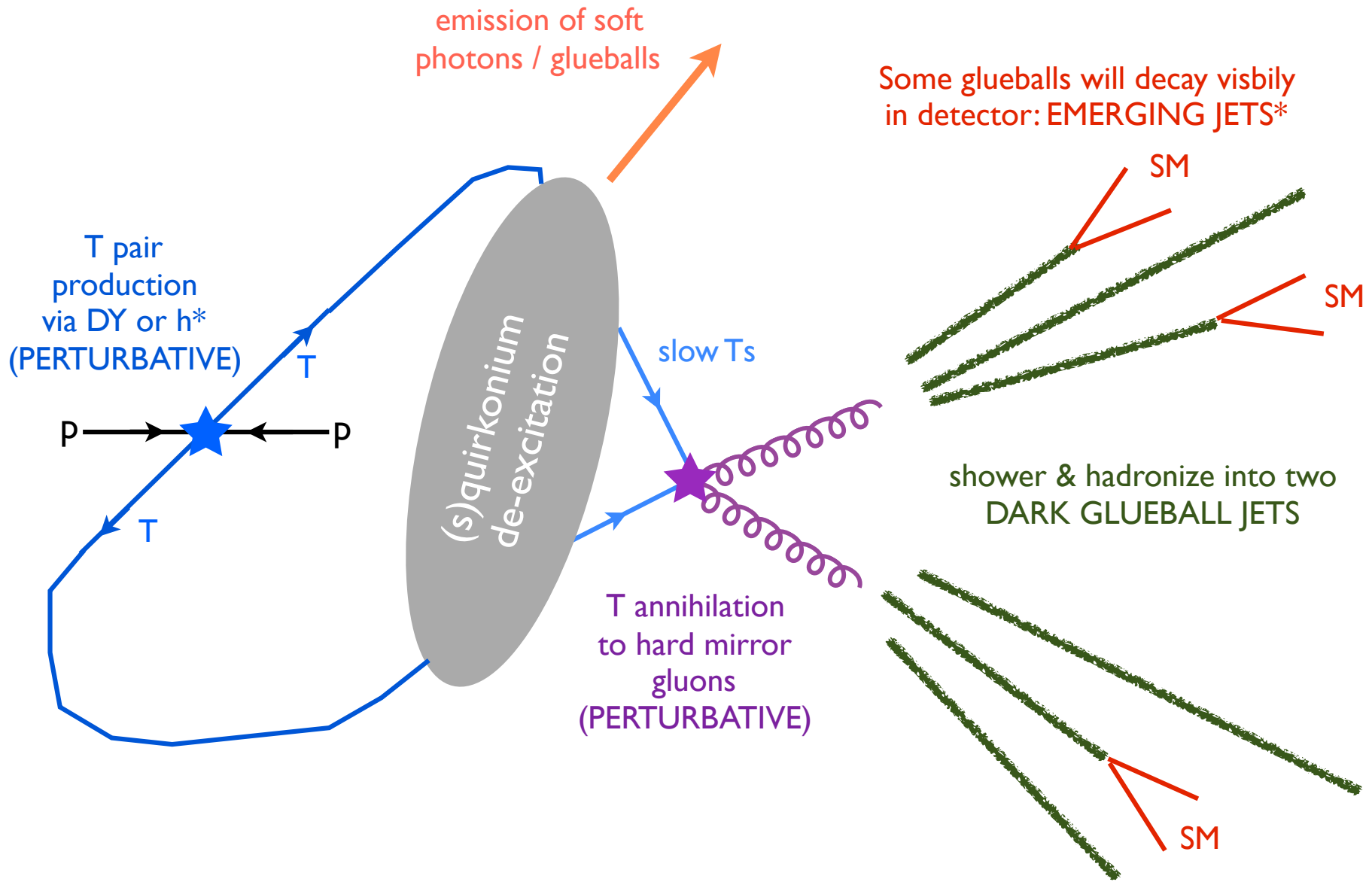
Top Partner Pair Production

(most important for EW partners e.g. FSUSY, QLH)

Top partner direct production



* see also 1502.05409 Schwaller, Stolarski, Weiler

Chacko, DC, Verhaaren, 1512.05782, more detailed collider study in progress…

Top partner direct production

Even qualitatively accurate description requires understanding of

(a) QQ bound state production and de-excitation

(b) pure-glue mirror hadronization

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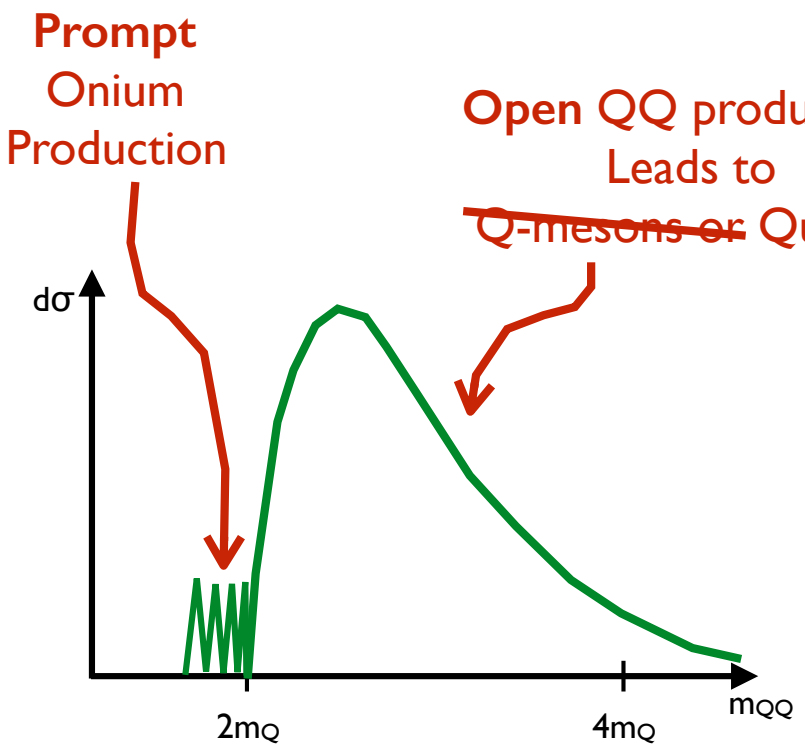
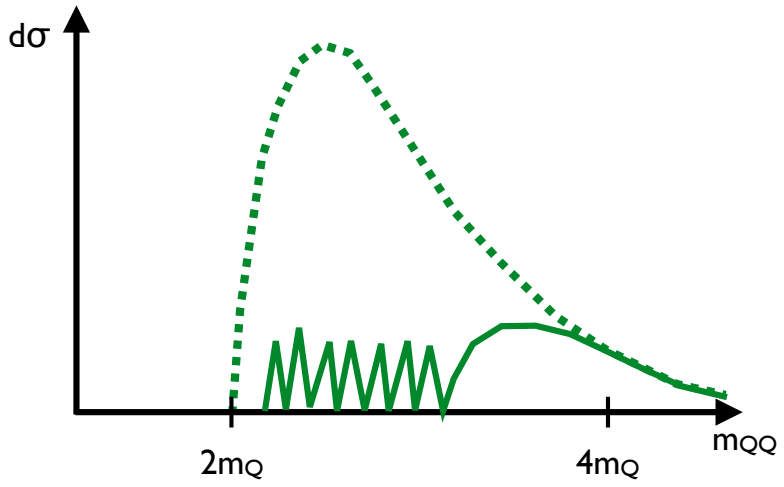


Can give additional signals.
Glueball fireballs?



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Even qualitatively accurate description requires understanding of

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TT annihilation

Chacko, DC, Verhaaren [ongoing]

Top partner direct production

Even qualitatively accurate description requires understanding of

(a) QQ bound state production and de-excitation

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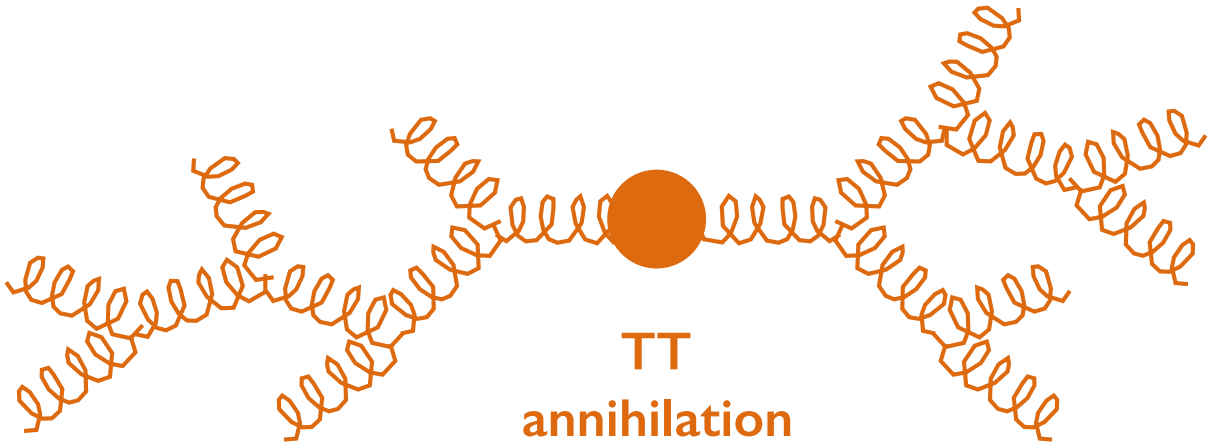
Implement perturbative gluon-only parton shower
(theoretically under control)

In Mathematica! :D



Chacko, DC, Verhaaren [ongoing]

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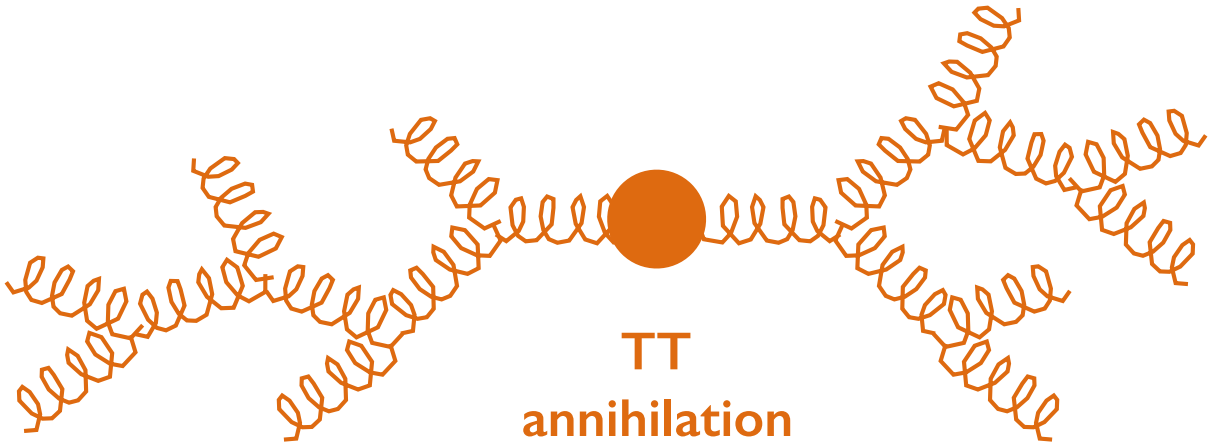
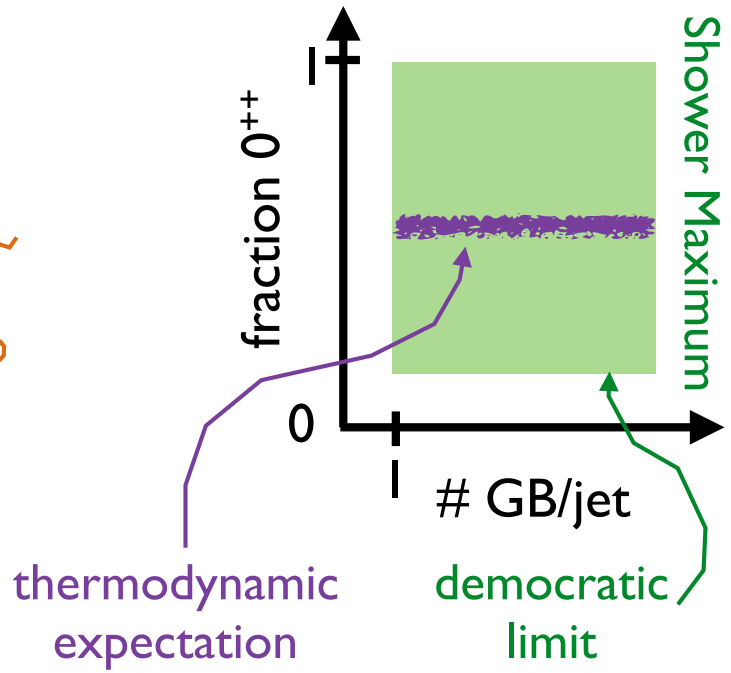
Toy hadronization model: parameterize our ignorance of non-perturbative dynamics with "honest" O(1) precision



Finite space of unknown fragmentation functions



Chacko, DC, Verhaaren [ongoing]

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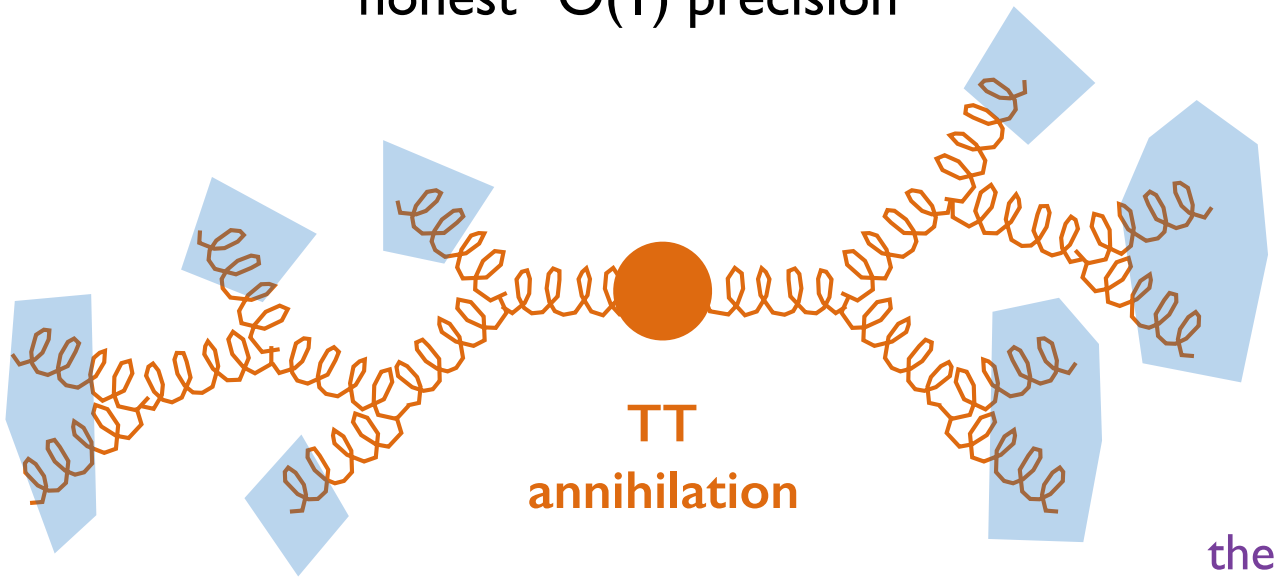

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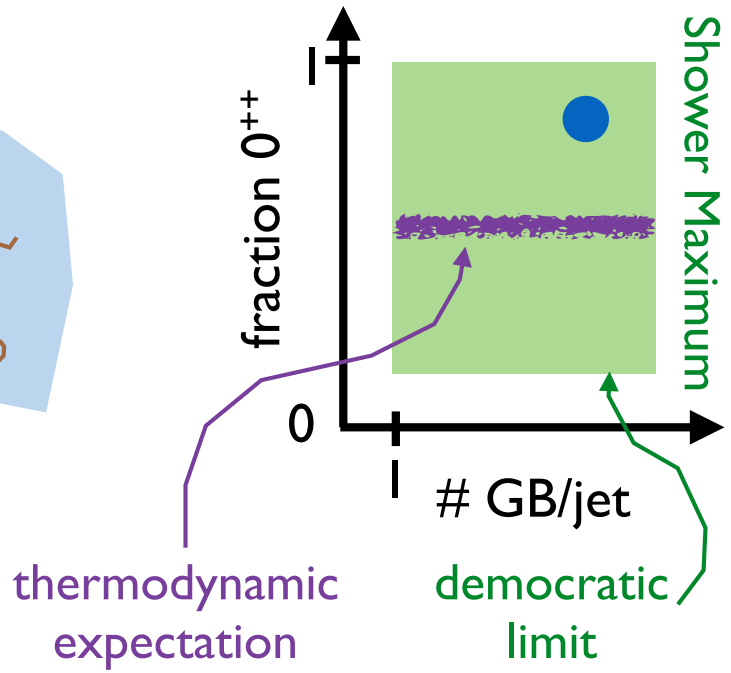


Chacko, DC, Verhaaren [ongoing]

Top partner direct production

Already showed that glueball signal from top partner pair production can be comparable or larger than from exotic Higgs decays

Different kinematics and high multiplicity may offer unique advantages for short lifetimes.

Chacko, DC, Verhaaren [ongoing]

Searches for LLPs:

Overview

For more details, see talks by
Eric, Henry, Jamie, John Paul

Neutral LLP Searches

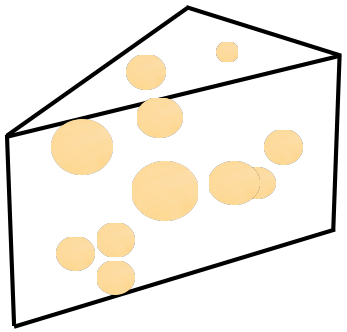
Neutral LLP searches are harder than charged LLP searches, but the signals can still be spectacular.

Distinctiveness of Signature in Detector:

Heavy charged track/ deposition > **Displaced Decay** > Missing Energy

not yet

more like



Rule of Thumb for Neutral LLP searches

DV + X ⇒ Very little background @ LHC

High quality very macroscopic **displaced vertex**

Something else that's kinda rare (leptons, high-mass, another DV…)

X could be a property of the LLP itself

Performed Searches at ATLAS or CMS

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High quality very macroscopic **displaced vertex**

Something else that's kinda rare (leptons, high-mass, another DV…)

$d \gtrsim$ cm **+** X = distinctive LLP decay products (leptons, lepton jets…)
X = 'hard' LLP: has high mass and decays in tracker
X = another DV, and first DV is in Muon System/HCAL
(longish lifetime)

Performed Searches at ATLAS or CMS

Very little

ground

LHC

High

very ma

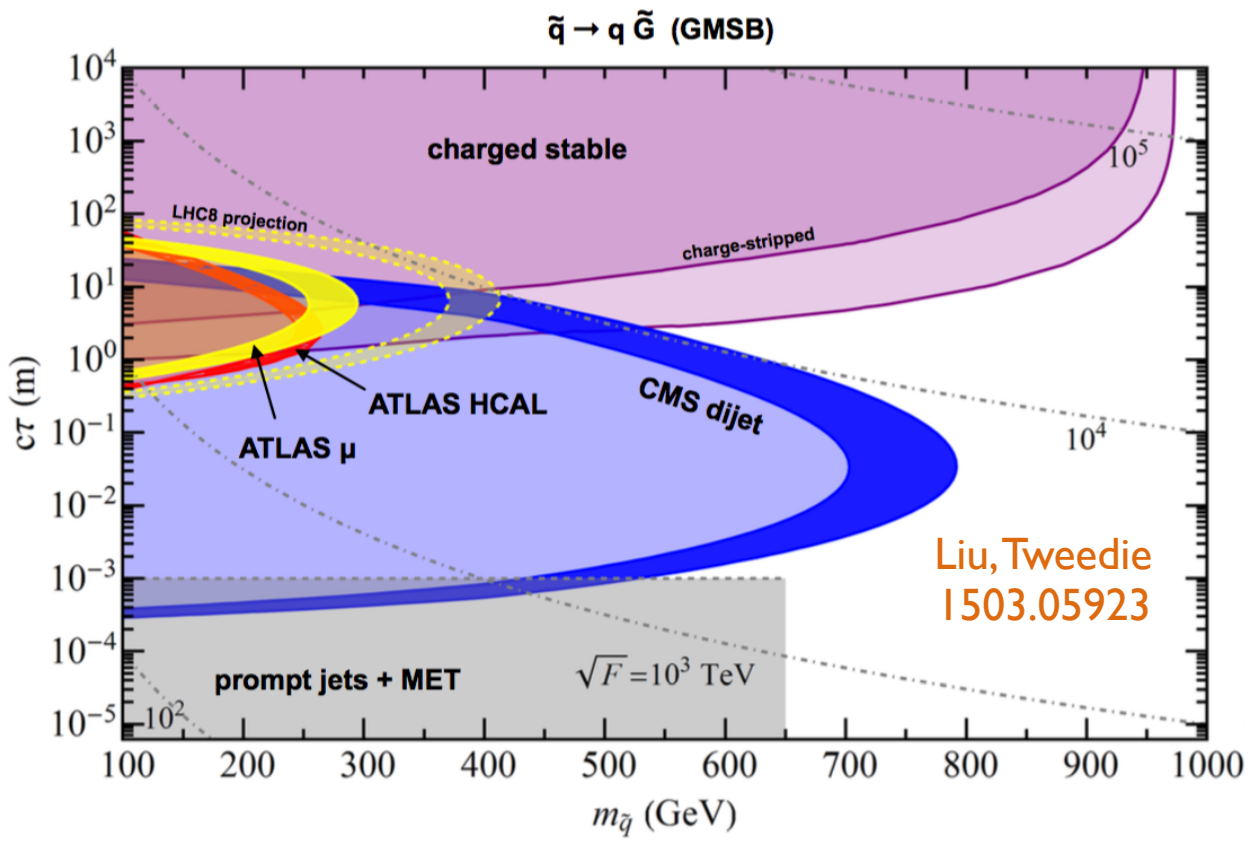
displace

d > cm +

epton jets…)

racker

em/HCAL



In combination, together with charged LLP and prompt searches, this already gives very significant reach for many theories!

Most important required searches

DV + X ⇒ Very little background @ LHC

High quality very macroscopic **displaced vertex**

Something else that's kinda rare (leptons, high-mass, another DV…)

1. Need sensitivity for "softer" LLPs, e.g. from **exotic Higgs decays, which is a highly motivated LLP production mode**
   ⇒ X = single lepton (Vh) or VBF jets *(events are on tape!)*

2. X = all of the above, **DV with d ~ 0.1mm - cm**
   (repurpose b-tagger? LHCb opportunity?)

3. LLP decay with **d >> detector size**
   (also relevant for testing if MET = DM)

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See Eric's talk

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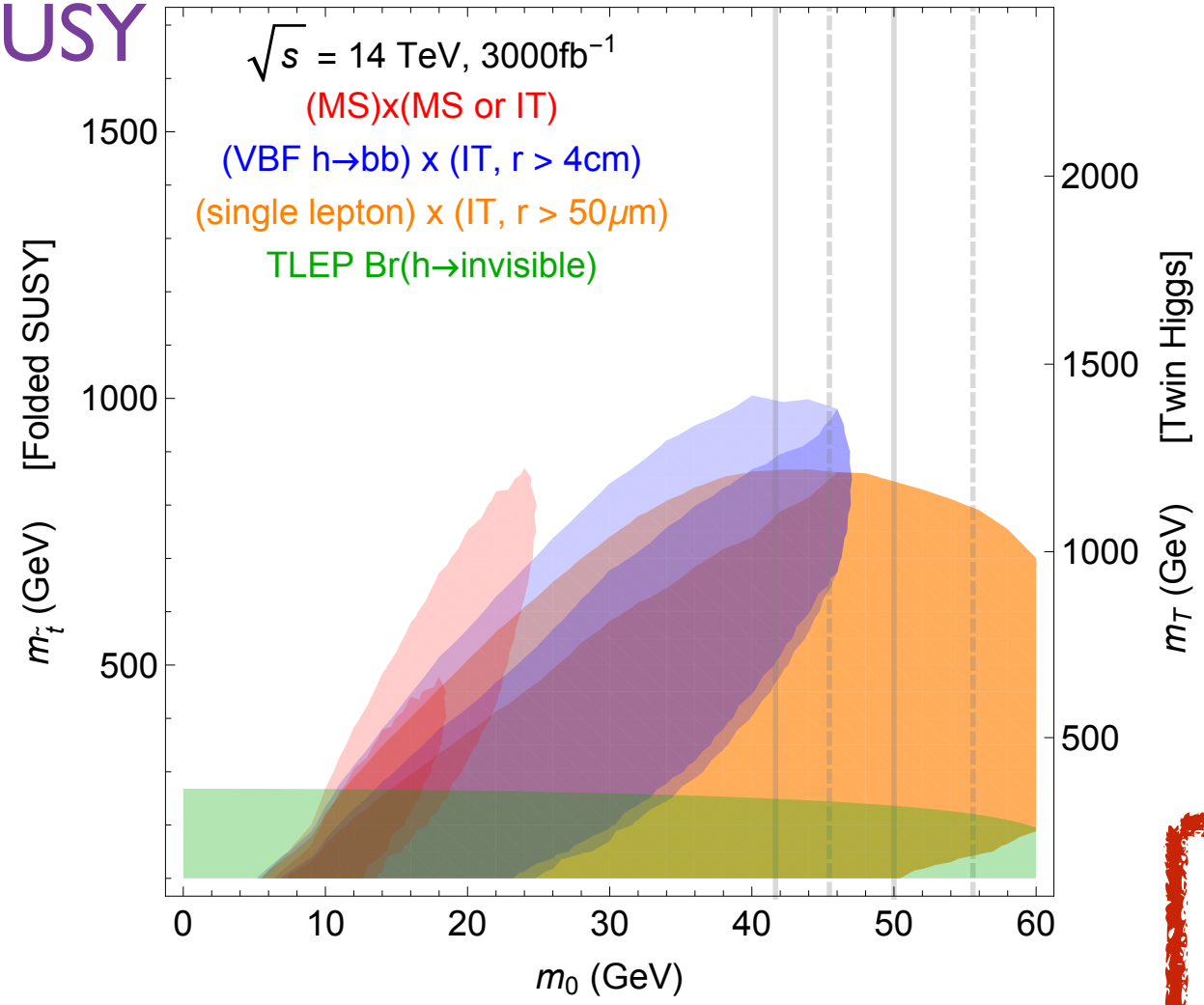
EW top partners @ HL-LHC

FSUSY

top partner mass



glueball mass

DV searches in tracker* or Muon System

**need VBF or lepton for triggering.*

TeV Top Partner Mass Reach from LLP searches!

DC, Verhaaren 1506.06141

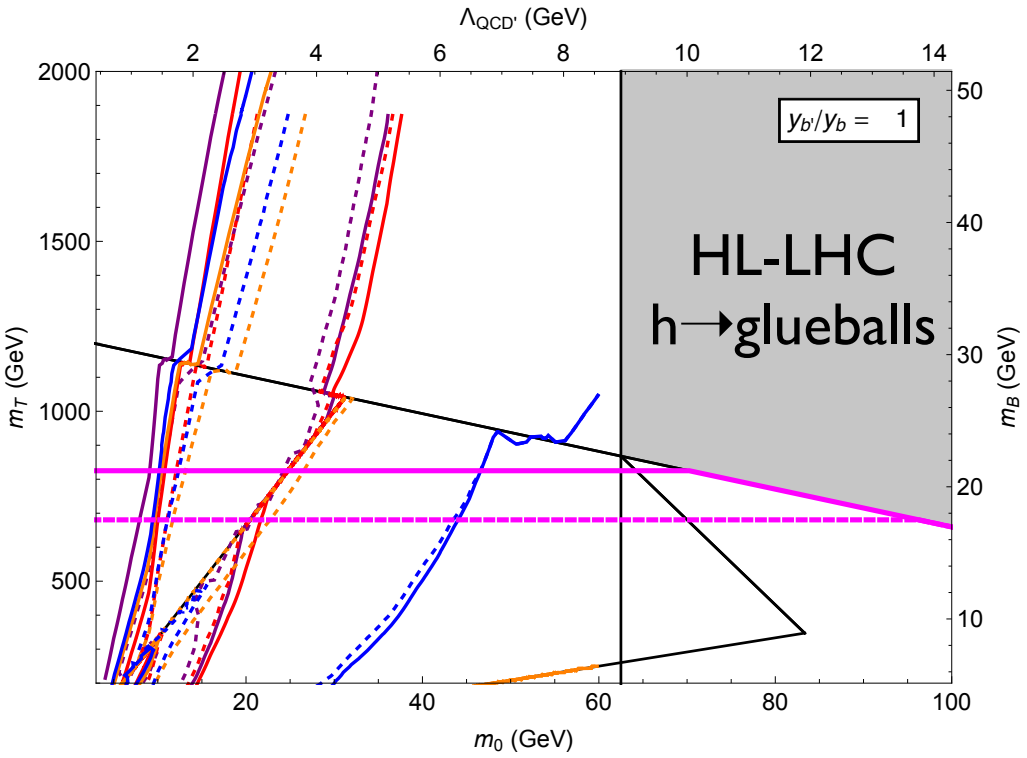
Preliminary

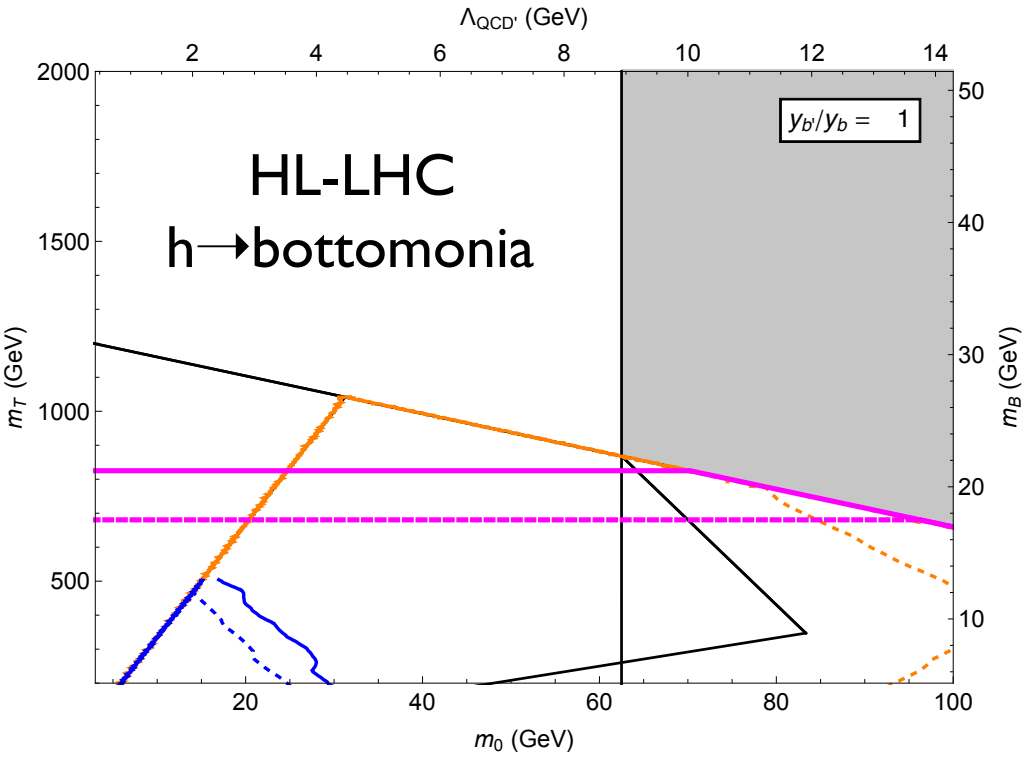
Neutral top partners @ HL-LHC

Coccaro, Curtin, Lubatti, Russell, Shelton1605.02742

DC, Tsai 1701.xxxxx

More complicated due to richer Hidden Sector spectrum including bottomonia. **HL-LHC still has TeV reach!**





1DV in MS

2DV in MS

1DV in tracker (r > 50μm) + lepton

1DV in tracker (r > 4cm) + vbf

Higgs coupling measurements (3000, 300/fb)

(heavy

1505.07109 Garcia Garcia, Lasenby, March-Russell

Most important required searches

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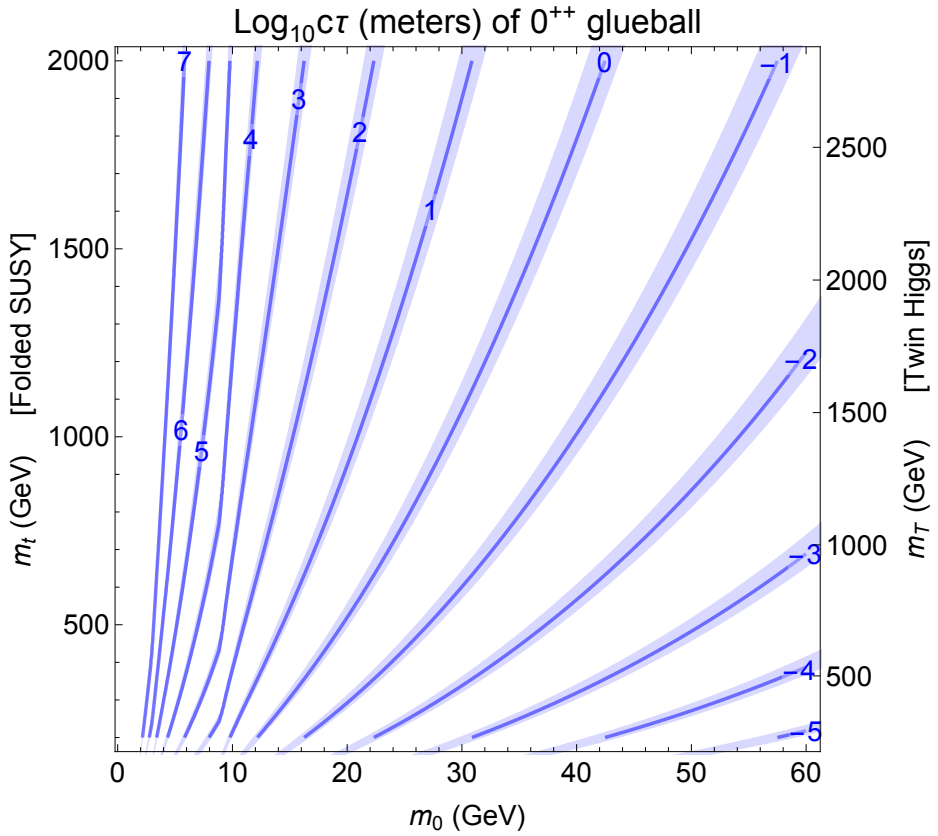
LLPs with very long lifetimes

At ATLAS: look for a single LLP in muon system.

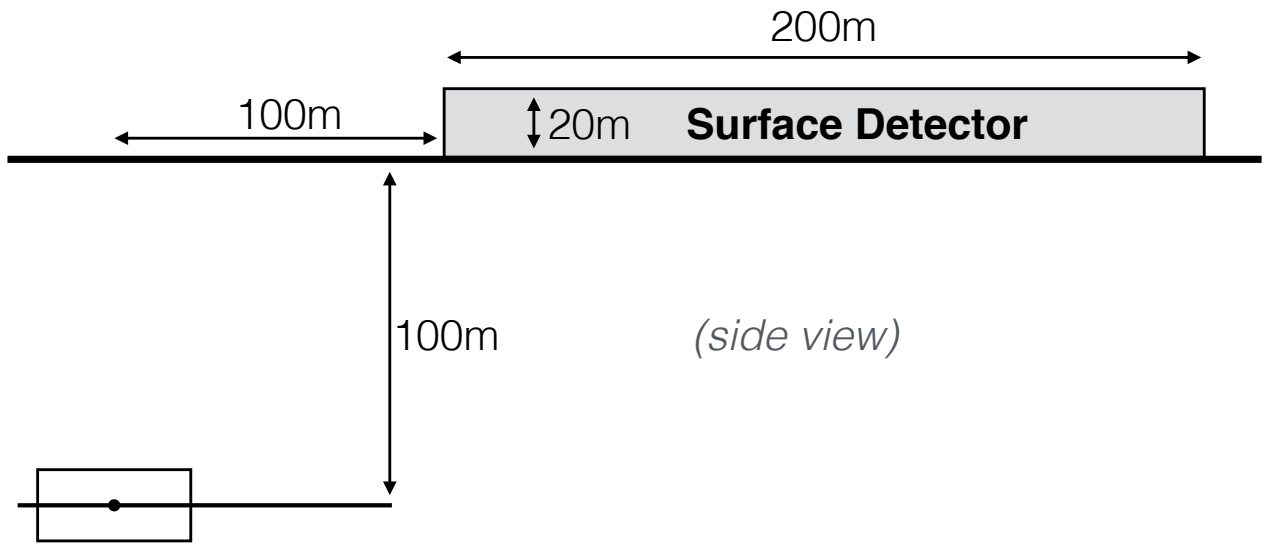
See Henry's Talk:
could access NN glueballs
in 5-10 GeV mass range.



LLPs with very very long lifetimes

See John Paul's talk: **MATHUSLA**

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles



John-Paul Chou
David Curtin
Henry Lubatti
1606.06298

Thank You!